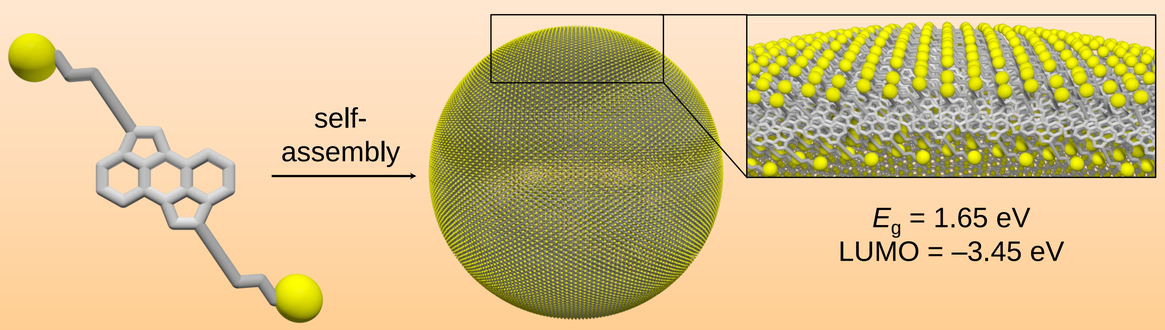
Self-Assembly of a Bolaamphiphilic Cyclopenta[*hi*]aceanthrylene Derivative in Aqueous Medium

Simon Rothenbühler, Simon M. Langenegger and Robert Häner

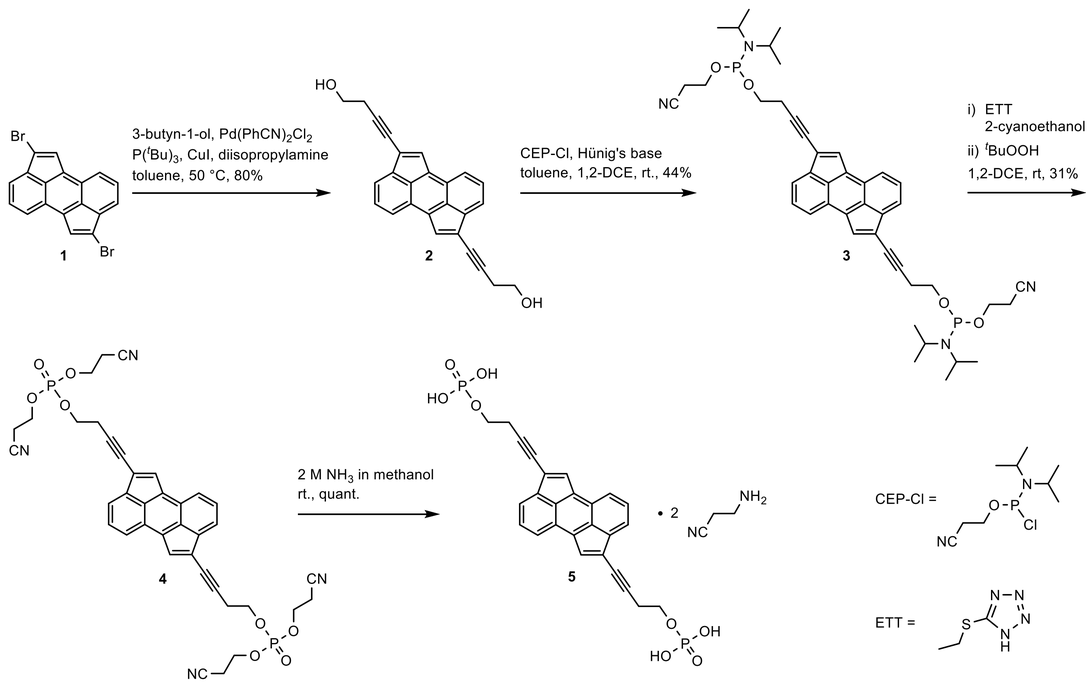
Department of Chemistry and Biochemistry, University of Bern, Freiestrasse 3, 3012 Bern, Switzerland
simon.rothenbuehler@dcb.unibe.ch

Abstract: The water-soluble, bolaamphiphilic cyclopenta[*hi*]aceanthrylene-bis-phosphate has been synthesized. This compound exhibits absorption over the entire visible spectral range and a low-lying LUMO. In aqueous medium, cypac-bis-phosphate self-assembles into a vesicular morphology and preserves the remarkable electronic properties of the monomer in the supramolecular assemblies.



1 Synthesis

Depicted in Scheme 1 is the synthesis of the target compound cyclopenta[*hi*]aceanthrylene-bis-phosphate (cypac-bis-phosphate) **5**. The synthesis of 2,7-dibromocypac **1** followed published procedures.[1] Sonogashira cross-coupling reaction yielded cypac-diol **2**. Both hydroxyl groups were phosphitylated to afford cypac-phosphoramidite **3**, which was reacted with 2-cyanoethanol using ETT as activator. The resulting phosphite triester was oxidized to the corresponding phosphate triester **4**. Cypac-bis-phosphate **5** was isolated after deprotection of the base-labile cyanoethyl ester groups.



Scheme 1 Synthesis of cypac-bis-phosphate **5**.

2 UV-vis spectroscopy

The UV-vis absorption spectrum of the intermediate cypac-diol **2** (Figure 1) can be divided into three distinct energy parts: an intense peak at 249 nm, a series of peaks between 350 nm and 500 nm, and a broad structureless absorption band in the long-wavelength region. Cypac-bis-phosphate **5**, molecularly dissolved in ethanol (Figure 2, black), exhibits the same absorption profile as cypac-diol **2**. In aqueous medium, the intensities of the absorption bands is reduced, without any significant shifts (Figure 2, red and blue). The hypochromic effect upon cooling the aqueous solution slowly from 75 °C to 20 °C indicates the formation of a supramolecular polymer *via* self-assembly. According to the onset of the lowest energy absorption band of **5** (750 nm), the optical bandgap (E_g) is 1.65 eV for the supramolecular polymer, as well as for the monomer **5** and is attributed to the HOMO-LUMO transition.[1]

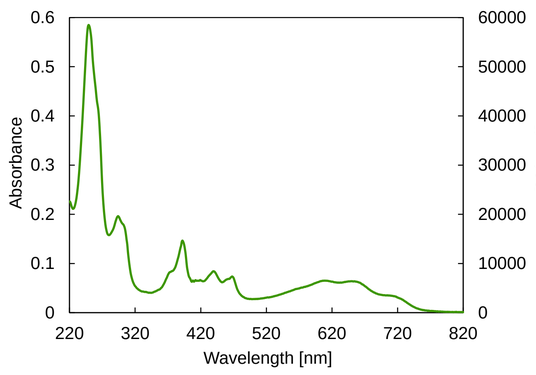


Figure 1 UV-vis absorption spectrum of cypac-diol **2**. Conditions: 10 µM of **2** in THF, 20 °C.

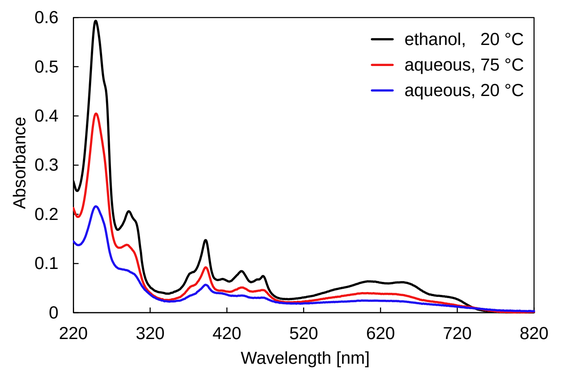


Figure 2 UV-vis absorption spectra of cypac-bis-phosphate **5**. Conditions: 10 µM of **5** in ethanol, as well as in aqueous medium (10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol).

3 AFM and TEM

As displayed in Figure 3, the self-assembly of cypac-bis-phosphate **5** leads to spherical objects. The spherical shape is supported by the AFM height profiles and the deflection scan, indicating that **5** self-assembles into vesicles. An increase in concentration of **5** from 5 µM up to 20 µM results in the formation of larger vesicles (not shown here). The TEM image of self-assembled **5** further confirms the vesicular morphology. All those observations lead to the suggestion that, due to hydrophobic interactions of **5** in aqueous medium, a membrane with π-stacked cypac cores inside of the layer is formed, while the negatively charged phosphate groups point towards the polar, aqueous environment (see abstract).

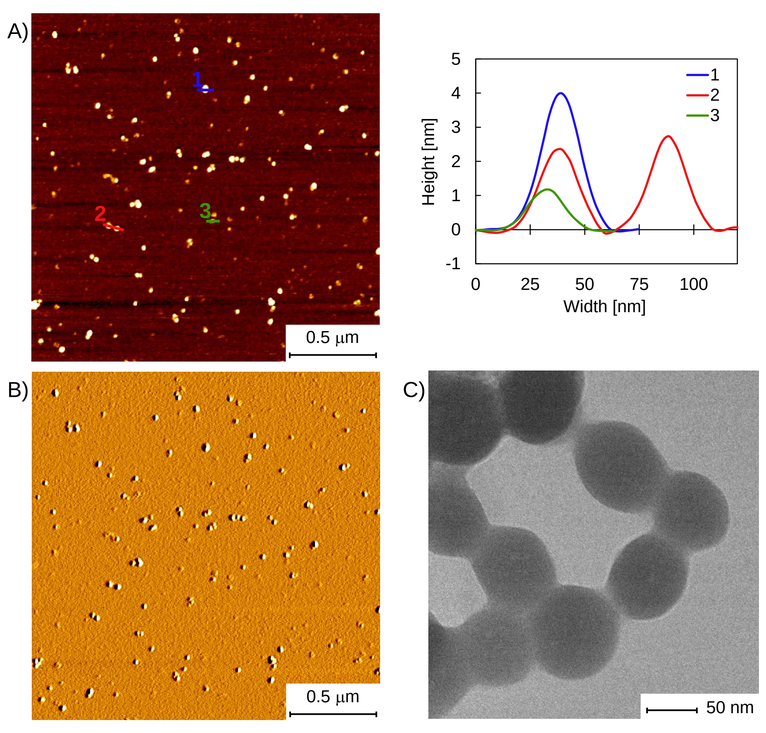


Figure 3 (A) AFM image with corresponding cross-sections of aggregated cypac-bis-phosphate **5** in aqueous medium deposited on APTES-modified mica. (B) AFM deflection scan. (C) TEM image of self-assemblies of cypac-bis-phosphate **5**.

4 Cyclic voltammetry

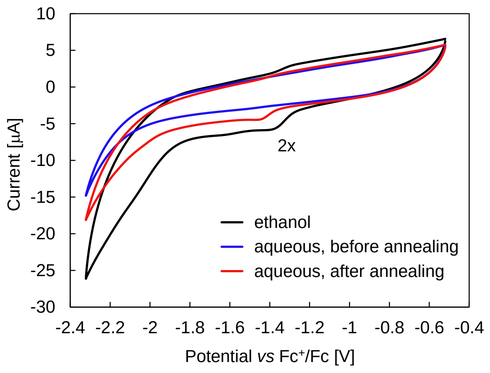


Figure 4 Cyclic voltammograms of cypac-bis-phosphate **5** in ethanol and aqueous medium at 20 °C. Concentration in ethanol: 0.5 mM of **5** in 0.1 M $NaClO_4$. Concentration in aqueous medium: 1 mM of **5** in 10 mM sodium phosphate buffer pH 7.0, 10 vol% ethanol.

Cyclic voltammetry (CV) was utilized to investigate the electrochemical properties of **5**. The obtained data allowed the assignment of the frontier orbital energy levels (Table 1). A nearly irreversible reduction wave is observed for **5** in ethanol (Figure 4, black). In aqueous medium, no reduction could be detected without performing a thermally controlled assembly process (Figure 4, blue). In this case, aggregates of **5** are randomly oriented and the resulting reduced species is not shielded from the surrounding water, which provokes a fast chemical follow-up reaction. In contrary, a thermally controlled annealing process results in the formation of a highly ordered supramolecular polymer that undergoes one irreversible reduction (Figure 4, red). In those ordered assemblies, the cypac cores are arranged in a π-stacked fashion that minimalizes the contact with water and thus, stabilizes the reduced species to some extent.

	E_g [eV]	$E_{red/onset}$ *vs* Fc^+/Fc [V]	LUMO [eV][a]	HOMO [eV][b]
ethanol	1.65	–1.25	–3.55	–5.20
aqueous, after annealing	1.65	–1.35	–3.45	–5.10

Table 1 Optical bandgap (E_g), electrochemical potential and frontier orbital energy levels of **5** in ethanol, as well as in aqueous medium. [a] $E_{LUMO} = [-e(E_{red/onset} + 4.8)]$ eV.[2] [b] $E_{HOMO} = [E_{LUMO} - E_g]$ eV.

5 DLS

Dynamic light scattering (DLS) experiments complemented AFM and TEM measurements by a solution-based method and confirmed the spherical shape of the supramolecular vesicles. The number particle size distribution (PSD) results (Table 2) are consistent with the AFM and TEM images and verified the concentration dependent size of the vesicles. Measuring the sample solutions at 70 °C, no distribution was displayed, which is a clear indication for the disassembly of the supramolecular polymer at this temperature.

Concentration of **5**	5 µM	10 µM	20 µM
Number PSD [d.nm]	21.15 (100%)	53.67 (99.9%)	59.06 (100%)

Table 2 DLS particle size distribution results of self-assembled cypac-bis-phosphate **5** in aqueous medium at 25 °C.

Conclusions

The synthesis of the water-soluble bolaamphiphile cypac-bis-phosphate **5** has been demonstrated. UV-vis absorption is observed over an extended UV-visible spectral range and a narrow HOMO-LUMO bandgap of 1.65 eV was calculated for this compound. In aqueous medium, cypac-bis-phosphate **5** self-assembles into supramolecular vesicles, which was evidenced by AFM, TEM and DLS experiments. A low-lying LUMO of –3.55 eV in ethanol and –3.45 eV in aqueous medium was estimated by cyclic voltammetry. Additionally, the CV data showed that the frontier orbital energy levels of **5** were not shifted considerably upon supramolecular polymer formation.

References

[1] J. D. Wood, J. L. Jellison, A. D. Finke, L. Wang, K. N. Plunkett, *J. Am. Chem. Soc.*, **2012**, 134, 15783-15789.

[2] C. Yi, C. Blum, M. Lehmann, S. Keller, S. X. Liu, G. Frei, A. Neels, J. Hauser, S. Schürch, S. Decurtins, *J. Org. Chem.*, **2010**, 75, 3350-3357.